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METHOD FOR DETERMINATION OF THE PRESTRESSING FORCE OF CONNECTING COMPONENTS BY ULTRASOUND EXCITATION

[0001] Technical field

[0002] The prestressing force of mechanical connecting components such as screws or bolts is checked by means of ultrasound measurement methods. This is done by measuring the signal delay time of ultrasound waves which are injected into the respective connecting component at one or more separate, frequently predefined, operating frequencies. In the course of the progress in material sciences, a large number of composite and graded materials as well as special alloys have been introduced in recent years, from which connecting components such as bolts or screws can be manufactured, but whose material characteristics place more stringent demands on a measurement method for determination of the prestressing force.

[0003] Prior art

[0004] In previously known ultrasound measurement methods, the signal delay time of ultrasound waves at one or more, separate, frequently predefined operating frequencies is measured in order to determine, for example, the screw prestressing force in a screw which is used as a connecting component.

[0005] Application of the known ultrasound measurement methods to the composite and graded materials as well as special alloys which have been introduced in recent years and

which have been based on the progress in material sciences frequently fails because the ultrasound frequency spectrum passing through the material of the connecting element varies to a major extent when there is an increased prestressing force or when relatively long screws are bent in the desired intended load area, and entire frequency bands are often absent, and are no longer available for measurement purposes. This means that these measurement methods, which are based on fixed predefined frequencies and/or narrow frequency ranges, produce unusable results in the absence of one or more frequency ranges.

[0006] By way of example, multiple frequency methods with two frequencies are used in the known methods for stressing force measurement by means of ultrasound echo methods. These multiple frequency methods have the disadvantage that, because of the characteristics of the material of a screw or of a bolt, reflections can occur on grain boundaries or other material structures in the area of the sound propagation path, and can lead to disruptive interference at the operating frequencies that are used. In the event of a change to screws or bolts as a result of the stressing force which in each case acts on them, the material characteristics can furthermore be changed such that the signals which can still be observed in the absence of a stressing force cannot be observed, or can be observed only inadequately, at the chosen operating frequencies when a stressing force has already been applied, or if the stressing force is variable. The resolution of the delay time measurement thus deteriorates as the stressing force in the connecting component is increased, or measurement of the delay time of the injected ultrasound echo even becomes impossible.

[0007] In the case of known methods, which are based on excitation with short pulses or flanks (stepped signals), a broadband signal is used because of the correspondingly wide

bandwidth which occurs with short signals. However, because of the stress limit with respect to the signal amplitudes or the signal power in the generation process, or because of restrictions to the detection f small signals after excitation on the same line, this broadband signal can be used only disadvantageously. The reason for this is that, as the transmission power is increased, the gain which is required for this purpose is also associated with an increase in the noise level, which has a disadvantageous effect on detection with an optimum signal-to-noise ratio. Furthermore, when the signal voltages are relatively high, only less advantageous switches or input amplifiers can be used. It should also be remembered that increasing the transmission power of amplifiers results in relatively high costs in order to provide high voltages and/or high power levels with components such as these.

[0008] DE 42 24 035 A1 and DE 42 32 254 A1 disclose an ultrasound test method. According to this method, a frequency-modulated chirp signal x(t) is provided in order to drive an ultrasound transducer arranged in a transmission path, and the instantaneous frequency f of this chirp signal x(t) is modulated non-linearly with the time t. The time profile f(t) of the instantaneous frequency f of the frequency-modulated chirp signal x(t) is matched to the transfer function H(f) on the predetermined transmission path. Changes over time in the instantaneous frequency f of the frequency-modulated chirp signal x(t) are correlated with the value of the transfer function H(f) of the transmission path associated with this frequency f, in such a manner that, at frequencies f with a low associated value of the transfer function H(f), the rate of frequency change is less than in the case of frequencies f with a high associated value of the transfer function H(f). A square-wave chirp signal x' (t) is used according to the solutions in DE 42 24 035 A1 and DE 42 32 254 A1 in order to drive the ultrasound transducer. A signal generator is used to drive the ultrasound transducer with a

frequency-modulated chirp signal x(t), whose instantaneous frequency f does not depend linearly on the time, and a pulse compression filter which is used for conversion of the chirp signal y(t) received by it or by some other ultrasound transducer to a short received pulse z(t).

[0009] Description of the Invention

[0010] In order to make it possible to keep the advantages of pulsed excitation, that is to say the bandwidth, and the amplitude (voltage) for the electrical excitation of the connecting component small in an advantageous manner, the invention proposes that the connecting component, such as a screw or a bolt, be excited with a broad bandwidth for an extended time, but with a length which can be adapted for observation of echoes. Although it is known for pulsed excitation to be carried out with a broad bandwidth, the advantages have, however, not yet been identified, since the output power (that is to say the power of the output amplifier) cannot be optimally used with short pulses or stepped signals, since the broadband characteristic is produced over extremely short signal sections (short pulses, small steps).

[0011] A digitally programmable arbitrary function generator whose signal waveform can be manipulated is used to select pulsed excitation, for a limited time, with a suitably predetermined pulse width and with a determined profile which varies over time (for example broadband noise). By way of example, broadband noise can be chosen which is structured such that, taking into account the usable bandwidth of the transducers that are being used, this includes all of the frequencies at approximately the same amplitude. At this point, reference should be made to the publication "An Ultrasonic Pseudorandom Signal-Correlation System", Charles M. Elias in IEEE Transactions on Sonics and Ultraconics, Vol.

SU-27, No. 1, January 1980, pages 1 to 6. This means that the ultrasound excitation pulse is used to excite a maximum excitable ultrasound frequency spectrum in which as many frequencies as are possible by virtue of the pulse width and the upper selected cut-off frequency are excited. This can also be done by means of differently structured pulses to the broadband noise mentioned above, for example as known from "Radar Design Principles", signal processing and the environment, Fred B. Nathanson, J. Patrick Reilly and Marvin N. Cohen, McGraw-Hill, Inc., New York, St. Louis, San Francisco, 1991, 1969, ISBN 0-07-046Q52-3, Chapter 8, pages 351 et seq. Because of the fact that a signal extended over time is used, this advantageously allows a relatively large amount of power to be introduced into the connecting component, with a relatively small signal amplitude. When using the method proposed according to the invention, voltages of between 2V and 5V are normally used in practice, while in the case of known methods the voltage values are typically around 100 V, and 400 times as much power is required. Because of the broadband characteristic, the method proposed according to the invention is also stable with respect to changes in the material characteristics of the connecting component resulting from the prestressing of the connecting component, in terms of attenuation or complete absence of individual frequency ranges, since the ultrasound frequency spectrum excites as many frequency ranges as possible.

[0012] In the example mentioned above, the ultrasound signals are chosen such that the amplitudes and the power in all of the frequency ranges, also integrated over the pulse width, have a profile which is as matched as possible. In this case, the phase angle for broadband noise varies randomly, or varies in a predetermined continuous manner in the case of other signals. For example, a broadband pulse with a noisy signal is produced with a pulsed power

distribution which is approximately square-wave over time (with respect to the time domain) as a result of the predetermined Or chosen bandwidth, which limits the rise time and the fall time of the pulse.

[0013] Since the signals which are injected into the connecting component, such as a screw or a bolt, are produced at a phase angle which is defined but varies over the frequency ranges, the phase information is available together with the amplitude information as a function of the frequency, so that they can be used in the evaluation of detected echo signals. At this point, reference should be made to the literature reference “Radar Design Principles”, “signal processing and the environment, Fred B. Nathanson, J. Patrick Reilly and Marvin N. Cohen, McGraw-Hill, Inc., New York, St. Louis, San Francisco, 1991, 1969, ISBN 0-07-046052-3, Chapter 12, pages 533 to 582, there.

[0014] Echo signals are used during detection for pulse compression. In contrast to the situation with analog methods, the pulse compression is in this case carried out after the digitizing of the methods, by means of suitable software on a computer basis.

[0015] The advantage of excitation, for example, using a pseudo-random noise signal or using signals with a random phase angle for the measurement of the prestressing force in connecting components such as screws is that the screws produce systematic but unpredictable delay time changes and reflections of the ultrasound signals, as a result of manufacturing- dependent scatters in production and unpredictable changes in the frequency response and phase response during the tightening process, and these lead to unpredictable damaging construction and reconstruction interference, interfering with the measurement. In

the case of unpredictable interference, a randomly distributed input signal (pseudo random noise) or a pseudo-random input signal is used in order to minimize such resultant interference. The advantage achieved in this way for measurement and for safety is particularly significant in the case of safety-relevant critical screw connections, for example in aviation.

[0016] In addition, linear chirp is advantageously suitable for use as an excitation signal since much of the interference and many of the disturbances which are observed in connecting components such as screws still lead to advantageous results with this method.

[0017] Drawing

[0018] The method proposed according to the invention will be described in more detail with reference to the drawing, in which:

[0019] Figure 1 shows one embodiment variant of an ultrasound measurement system with a circulator, a switch or a reflectometer or an electrical connection.

[0020] Embodiment Variants

[0021] The illustration in figure 1 shows, schematically, one embodiment variant of an ultrasound measurement system for connecting components, such as screws. A component which is annotated with the reference symbol Z may be represented either as a circulator, as a switch, as a reflectometer or as an electrical connection.

[0022] In the following text: the expression “pseudo-random noise” (pm) means a signal which satisfies one or more 35 tests for random distribution. Although the signal appears to lack any defined pattern, a pseudo-random noise signal contains a frequency of pulses which are repeated but only after a relatively long time or a relatively long pulse sequence.

[0023] The connecting component 1, which is in the form of a screw and as illustrated in figure 1, has a screw head 2 as well as a shank 3. A threaded part 4 runs underneath the shank 3. A transducer 5 f or an ultrasound pulse 7, which is in the form of a chirp pulse, is located on the screw head 2. Chirp pulses are pulses such as linear chirp pulses which have frequencies whose centroid rises or falls linearly as a function of the frequency with the time from the start of the pulse. The chirp method makes it possible to achieve time compression during detection, resulting in a minimum pulse width for the transducer. Furthermore, delta-pulse production from limited-frequency signal spectra is feasible, by the superimposition of a large number of sinusoidal or cosinusoidal partial waves around the phase 0° or 180° (Π) in the case of a cosine function. In the most general case, the signal components can be represented by an exponential function in the form $e(^{j\omega t})$. The greater the number of frequencies involved in the excitation, the stronger is the maximum or the more pronounced is the maximum which can be observed after compression. Compression is carried out after the digitizing of the received signal by means of a computer and computer programs. In this case, the received signal is first of all subjected to Fourier transformation. The phases of the spectral components are then shifted such that the phase angle 0 is obtained in the absence of the prestressing force in a representation using cosine functions for a time which is defined with respect to the excitation time. After back-transformation, this results in a compressed pulse with a marked maximum amplitude at this time. The position of the signal with the

maximum amplitude is determined by adaptation of one half-cycle in the vicinity of this maximum. The shifting of the spectral components and the form of the matching function are chosen to be the same for all prestressing forces for the respective connecting component 1. The delay time differences which are used to determine the prestressing force are obtained by forming the difference between the measurement of the result and the measurement without any prestressing force. The relationship between the prestressing force and any observed delay time differences for the respective connecting component 1 or a batch thereof is determined empirically by means of tensioning machines which allow a precise amount of stressing force to be applied. The respective individual measurement is evaluated, and the stressing force indicated, by means of the relationship determined in this way.

[0024] The transducer 5 as shown in figure 1 has an electrode 5.1 to which the signal line is connected, as well as a protective layer 5.2 located underneath it. A piezoelectric thin film 5.3 is located underneath the protective layer 5.2 and the upper face of the screw head 2. The reference symbol 6 denotes the propagation path of the ultrasound pulse 7, which is injected at the transducer 5, through the connecting element 1, which is in the form of a screw. The transducer 5 for the ultrasound pulse 7 at the same time represents the output point for an ultrasound pulse echo 8. The time which passes between the injection of an ultrasound pulse 7 at the transducer 5 into the connecting component 1, which is in the form of a screw, and the outputting of the ultrasound pulse echo 8, likewise at the transducer 5, is indicated by t.

[0025] The component, which is annotated Z and may be a circulator, a switch, a reflectometer or an electrical connection: gets into the signal transmission line between the connecting component 1, which is in the form of a screw, of a screw, to the arbitrary function

generator AFG and an amplifier V. An amplifier V is connected at 2, and is followed by a transient recorder TR. This is connected to a computer PC, which itself drives the arbitrary function generator AFO. The arbitrary function generator AFG is itself connected to Z. A repetition rate generator RG controls the transient recorder TR and the arbitrary function generator AFG. A clock transmitter TG controls the arbitrary function generator AFG, the transient recorder TR and the repetition rate generator RG. The PC is connected by data lines to the arbitrary function generator AFO and to the transient recorder TR.

[0026] The ultrasound pulse 7 illustrated in figure 1 is produced by means of the arbitrary function generator AFG. The computer PC provides the settings as well as data acquisition and its processing. The ultrasound pulse 7 represents a limited-time, pulsed excitation with a suitably variable pulse width and determined broadband "white" noise. The mean value of the amplitude over time remains constant, seen over the frequency band, in the case of broadband "white" noise.

[0027] Taking account of the usable bandwidth of the transducers 5 that are used, the ultrasound pulse 7 contains all of the frequencies with approximately the same amplitude. However, the phase angles are chosen so that the amplitudes and the power in all of the frequency ranges has as uniform a profile as possible over the pulse width. The predetermined or selected bandwidth, which in the end limits the rise and fall time of the broadband pulse, results in a pulsed power distribution with a noisy signal, with a profile which is approximately in the form of a square wave over time.

[0028] Since the ultrasound pulses 7 to be injected into the connecting component 1 re produced with a phase which is fixed but varies over the frequency ranges, the phase information (together with the signal amplitudes) is available as a function of the frequencies of the ultrasound frequency spectrum, in order that this information can be used for the evaluation of the detected, digitized ultrasound pulse echo 8.

[0029] As described above, during the detection of the ultrasound pulse echoes 8 once pulsed excitation has been carried out with an ultrasound pulse 7, the signals are digitized on a time-resolved basis via a transient recorder TR and are made available to a connected computer, such as a PC or a laptop. A digitally operating transient recorder TR may advantageously be used for the transient recorder TR. The signals, which are generally subject to considerable or severe noise, are compressed using the known phase angles after detection and digitization in the limited-time region, which can thus be selected, of the ultrasound pulse echoes 8 to be observed with the aid of Fourier methods, for example a Fast Fourier Transform (FFT).

[0030] During the detection, the transformation is carried out by means of a Fourier method such as FFT. The compression is carried out by means of computers and computer programs after the digitization of the received signal. In this case, the received signal is first of all Fourier-transformed. The spectral components then have their phases shifted such that this results in a phase angle of 0 in the absence of the prestressing force in a representation by means of cosine functions for a time which is defined with reference to the excitation time. After back- transformation, this results in a compressed pulse with a marked maximum amplitude at this time. The position of the signal with the maximum amplitude is determined

by adaptation of one half-cycle in the vicinity of this maximum. The shifting of the spectral components and the form of the matching function are chosen to be the same for all prestressing forces for the respective connecting component 1. The delay time differences which are used to determine the prestressing force are obtained by forming the difference between the results from the measurement from the stressing force. The relationship between the prestressing force and the observed delay time differences of the respectiie connecting component 1 or a batch thereof is determined empirically by means of tensioning machines, which allow a stressing force to be applied with precise amplitude. The respective individual measurement is evaluated, and the stressing force indicated, by means of the relationship determined in this way.

[0031] The method proposed according to the invention uses all of the frequency components of the signals which can be detected and can still be transported over the ultrasound path, that is to say the propagation path 6 of the ultrasound pulse 7, with the aid of the transducer 5 that is used, in each case with the maximum possible amplitude in all of the frequency ranges that are used.

[0032] In contrast to already known ultrasound measurement methods for measurement of reflection, in which signals which last over time are used, the (pulsed) excitation for a limited time which is used on the basis of the method proposed according to the invention makes it possible to select the contributions of different ultrasound pulse echoes 8, for example transversal, longitudinal first, second, n-th echo before the further processing, that is to say before compression, in the time domain, that is to say cut out of the measurement data. The known ultrasound measurement methods for measurement of the reflection, in which signals

which last over time are used, are methods with a low frequency for electronic spectrometers, which include phase measurement and in consequence are extremely sensitive to measurement time.

[0033] If the ultrasound signal delay times t are short, for example as is the case when the connecting components 1 are in the form of short screws, arid/or when the transducers 5 operate with a particularly broad bandwidth, the bandwidth to be used can also advantageously be distributed between a plurality of successive pulsed excitations. The distribution of the bandwidth to be used between a plurality of successive pulsed excitations may be randomly linear or may be achieved in some other way, for example by weighting specific bandwidth areas. A phase angle which is defined for the ultrasound pulse 7, that is to say for example with respect to its pulse center, is in each case chosen on the basis of the frequency interval which can still be resolved by means of a Fourier method, such as FFT or some other classical resolution method, and is associated therewith. The phase angle which is in each case associated with the ultrasound pulse 7 is therefore also known during the further processing and, in particular, during the evaluation in the course of the compression of the signals.

[0034] By way of example, the first, the second and the third third of the overall bandwidth may be used in three respectively successive and then repeated excitations, depending on the performance of the transducers 5 that are used. During the evaluation of the signals, that is to say the signal compression, the contributions of the three thirds that have been mentioned can be added up. This allows a compressed signal of optimum short duration and with a high signal amplitude to be generated from the data. In principle, a random distribution over any

desired number of ultrasound pulses 7 or any other distribution with a phase which is defined with respect to the ultrasound pulses 7 of all the resolvable and/or used frequency intervals is also possible and, if required, can be used advantageously.

[0035] Instead of the centroids of the frequency components involved being distributed linearly in time as in the case of the linear chirp, they may also be randomly distributed. This is the case for signals from thermal excitation and can also be carried out in a determined manner by appropriately synthesized signals, and the arbitrary function generator AFG can also be used to generate such deterministic, noise-like signals, which are also referred to as pseudo-random noise (prn).

[0036] One special case of pseudo-random noise (prn) is a noisy signal in which the amplitudes of the spectral components are kept as constant as possible, but the phase fluctuates randomly in a determined manner in the synthesis process. A signal such as this is in this case referred to as an electrical pulse 7 with predetermined pseudo-random phase angles.

List of reference symbols

1 Connecting component (screw, bolt)

2 Screw head

3 Screw shank

4 Threaded part

5 Transducer

5.1 Electrode

5.2 Protective layer

5.3 Piezoelectric thin film

6 ultrasound pulse propagation path

7 ultrasound pulse

t Time between the ultrasound pulse injection and the ultrasound pulse echo output

8 ultrasound pulse echo

Z Circulator, switch, reflectometer or electrical connection

AFG Arbitrary function generator

PC Computer

V Amplifier

TR Transient recorder

TG Clock transmitter

RG Repetition rate generator

TO Clock transmitter (clock)